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Rural-to-Urban Water Transfers: Measuring Direct Foregone Benefits of Irrigation Water under Uncertain Water Supplies

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Irrigation water from a southeastern Colorado county has been sold to distant municipalities. The county's junior water right delivered limited and uncertain water supplies which were used on relatively poor soils. The ability of water markets to allocate water to the highest-valued use was addressed by assessing the direct foregone benefits of the transfer using deterministic and discrete stochastic sequential (DSSP) programming models. Crop mix predicted by the DSSP followed observed regional patterns. The DSSP was thus used to derive regional water demand from which foregone value was estimated. Direct regional foregone agricultural benefits were relatively low—due to uncertain water supplies and unproductive soils—indicating the market selected a low-valued supply for transfer.

Key words: agricultural-to-urban water transfers, discrete sequential stochastic programming, regional irrigation water demand

Introduction

Irrigated agriculture uses 86% of the water consumed in the western states (Office of Technology Assessment). As residential, industrial, instream, and environmental demands for water increase and inexpensive sites for construction and storage of water have been exhausted, water transfers from agriculture emerge as a least-cost alternative to meet these competing demands. Water market institutions are evolving in the western states to accomplish these transfers (Saliba and Bush; Howe, Shurmeier, and Shaw). However, emerging water market transfers have raised concerns as to whether purchasing agricultural water for nonagricultural use benefits society (U.S. National Research Council).

Water transfers are economically justified if new benefits, minus conveyance and transaction costs, exceed foregone benefits (Young). Measuring benefits of foregone economic value of irrigation water is key in the economic assessments of water transfer proposals. Agriculture-to-urban transfers invert traditional benefit-cost ratios used to assess water policies. Historically, agriculture was the beneficiary of augmented water supplies, but in evaluating market transfers, agricultural water use becomes society's direct foregone benefit or opportunity cost of meeting new water demands. The benefit-cost calculation, from society's stance, requires a nonmarket analysis of foregone economic benefits. There is concern that water markets do not allocate water to the highest-valued use: sale prices

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may not reflect full social opportunity costs. Actual sales prices may vary with participants' knowledge of the market, with financial constraints or distress, or with collaboration of buyers or sellers to overstate or understate actual social costs. In addition to the following ex post evaluation, a nonmarket valuation can also be used ex ante to evaluate the social costs of future water transfers.

The conceptual basis for measuring foregone net irrigation water benefit is the same as for measuring increments of water supplies. Assuming producers are price takers in factor and product markets, net welfare or benefit loss is measured by the input demand function (Freeman and Harrington). For irrigation water, Lynne classified applied methods for approximating the input demand function as either analytical or aggregate. Analytical methods use experimentally based agronomic production function studies for individual crops (e.g., Hoyt). Aggregate methods, which attempt to measure regional irrigation water demands with econometric (e.g., Madariaga and McConnell) or programming methods, are appropriate to our case study. Mathematical programming techniques evolved from imputing the residual value of water using farm budgets. Agronomic plot data on irrigated crop response (the analytic approach) are incorporated into aggregate regional programming models. Recent programming approaches have made crop choices, irrigation timing and amounts, and irrigation technology endogenous to the models.[1]

Our research determined direct foregone economic benefits of agricultural water use on acreage served by the Colorado Canal, in Crowley County in southeast Colorado. Since the early 1970s, the water rights for over 90% of the 47,000 original irrigated acres served by the Colorado Canal were purchased by rapidly growing communities along the Colorado Front Range. Early purchases were primarily made by an investor group which paid a substantial premium above the going market rate, buying numerous farms during a period of depressed land prices. The group eventually sold the water rights. Many later sales, when farmers gained information and bargaining power, were directly from farmers to urban entities at greater prices (see Saliba and Bush or U.S. National Research Council for descriptions of Colorado Canal water sales). After the water purchases, municipalities continue to lease unneeded water back to farmers. The sale of the Colorado Canal is the latest and largest of five transactions from the Arkansas River basin (Howe, Lazo, and Weber); nine more Arkansas River diversion ditches, both larger and smaller than the Colorado Canal, are likely candidates.

Irrigated farming with the Colorado Canal began relatively late in the history of Arkansas Valley settlement, after early water rights were claimed for use on better soils with more accessible diversions. Consequently, the Colorado Canal has junior rights with highly variable deliveries. All irrigation water supplies in Crowley County are diverted, with considerable seepage loss, from the Arkansas River via the thirty-mile earthen Colorado Canal. Nearly half of the irrigated soils are alkaline, which diminishes yields of the principal crops—corn, alfalfa, and sorghum. Furthermore, rainfall in this arid region is limited and highly variable.

Accurately modeling Colorado Canal irrigation demand requires incorporating the analytic detail about crop production, with farmers' decision processes into an aggregate regional model that captures the specifics of Crowley County. Site-specific crop production

[1]Early efforts to model applied irrigation planning used linear programming to study the effects of changing water price and supply on optimal cropping patterns (e.g., Hartman and Whittlesey). Later efforts incorporated intraseasonal irrigation decisions, adapting quadratic programming (Howitt, Watson, and Adams) and dynamic programming (McGuckin et al.), although linear programming remains in current use (Bernardo et al.; Kulshreshtha and Tewari).

functions, variations in soil productivities, and regional irrigation and precipitation constraints are incorporated into a framework that accounts for the sequential nature of crop production decisions and the uncertainty in water supplies and rainfall. A deterministic model, representing average conditions of water supply, precipitation, and soil productivity, could not explain actual agricultural production in the region. We therefore developed a discrete sequential stochastic program (DSSP) which models the sequential and uncertain crop production process with regional constraints on soils and uncertain irrigation and rainfall to derive irrigation water demand in the case study region. Our focus on foregone direct net benefits complements the study of state-level economic impacts of water transfers from the Colorado Canal using input-output models by Howe, Lazo, and Weber. Our method of incorporating analytic crop production with decision choices into an aggregate model contrasts with their use of a synthetic input-output model to estimate direct as well as indirect impacts. Following detailed formulation of the model, data sources are described. To assess accuracy in regional irrigation demand, DSSP primal results are compared to actual regional crop production and contrasted with deterministic linear programming model results. DSSP dual results are then used to derive demand for uncertain water from which foregone benefits are estimated.

Model

Crop production is a sequential closed-loop process (Antle 1983a), such that: (*a*) planting, irrigating, and harvesting decisions are sequentially dependent; (*b*) information on irrigation and precipitation availability is feedback to be used in subsequent decisions; and (*c*) decisions are revised as new information becomes available. We have adopted Antle's (1983b) view that dynamic, risk-neutral models are more useful in understanding production risk in farm management than static risk-averse models. Through the dynamic production process, production risk determines farmers' optimal decisions for irrigation water and related inputs. Prediction of irrigation demand should incorporate risk if the objective function depends on the probability distributions of random variables and the farmer incorporates these distributions into decision making (cf. Antle 1983b).

DSSP was developed by Cocks to solve sequential decision problems under uncertainty.[2] DSSP is a programming technique that optimizes decisions over the paths of expected occurrences of multiple stages where the objective function, input-output coefficients, or resource constraints are uncertain (McCarl). Each decision stage is conditional upon past decisions and expected future events. DSSP was chosen over other stochastic dynamic techniques, such as stochastic dynamic programming, for this planning model because: (*a*) DSSP manages the dimensionality problem resulting from various states of nature for irrigation and precipitation, variations in soil productivity, multiple crops, and alternative irrigation intensities; (*b*) DSSP can account for risk in the objective function, as well as in the coefficients and resource constraints; and (*c*) the DSSP model can be readily solved with linear programming on a personal computer.

Farmers in the study region plant alfalfa, corn, and sorghum without knowing whether or not they will receive adequate irrigation water or precipitation. As the growing season

[2]DSSP was later applied in detail to agricultural decisions by Rae (1971a, b). Since then, DSSP has been adapted to study various agricultural decisions, including farm program participation (Kaiser and Apland), range improvements (Garoian, Conner, and Scrifres), and calf retention (Lambert).

progresses, the farmer learns how much irrigation water will be delivered. At season's end, following the outcome of uncertain growing season precipitation, farmers harvest crops. The three categories of activities in the DSSP model are the sequential stages in the decision tree for regional crop production: (*a*) planting and preplanting irrigation, (*b*) growing season irrigation, and (*c*) harvest and sales. Planting is the first stage in the sequential decision process. Planting and the preplant irrigation must be undertaken before irrigation water availability or precipitation is known. The second stage commences when canal diversions for the growing season become known. The third stage begins at the end of the growing season, when crop yields have been determined. After irrigation and precipitation have determined yields, producers must decide which crops to harvest and sell.

The DSSP model maximizes expected regional income over three sequential stages, subject to acreage, agronomic, soil quality, and irrigation water constraints:

$$(1) \qquad \max \sum_{j=1}^{4}\sum_{k=1}^{3} - C1_k X1_{jk} + \sum_{j=1}^{4}\sum_{k=1}^{3}\sum_{l=1}^{3} - C2_{jkl}\,[\sum_{m=1}^{2} P1_m X2_{jklm}]$$
$$+ \sum_{j=1}^{4}\sum_{k=1}^{3}\sum_{l=1}^{3} C3_{jkl}[\sum_{m=1}^{2}\sum_{n=1}^{2} P1_m P2_n X3_{jklmn}],$$

$$\text{s.t.:} \quad \sum_{k=1}^{3} X1_{jk} \le R1_j \; (j = 1, \ldots, 4).$$

$$\sum_{k=1}^{3} B_k X1_{jk} \le 0,$$

$$\sum_{k=1}^{3} A1_k X1_{jk} + \sum_{k=1}^{3}\sum_{l=1}^{3}\sum_{m=1}^{2} A2_{klm} X2_{jklm} \le R2_m \quad (m = 1, \ldots, 2),$$

$$X1_{jk} - X2_{jklm} = 0,$$

$$X2_{jklm} - X3_{jklm} = 0,$$

$$X \ge 0,$$

where $X1$ are the planting and preplant irrigation stage 1 activities; $X2$ are the growing season irrigation stage 2 activities; and $X3$ are the harvest and selling stage 3 activities. $A1$ and $A2$ are the water use coefficients for preplant and growing season irrigation, respectively. $R1$ and $R2$ are resource constraints on soil acreage and canal diversions, respectively. B is the minimum crop rotation. $P1$, $P2$, and $P3$ are the probabilities of each state of nature. $C1$ are planting costs. $C2$ are labor costs of growing season irrigation. $C3$ is revenue, net of harvest costs. Indexes are defined as the following: soil type $j(j = 1, \ldots, 4)$ with 1 = highly productive, 2 = less fertile and higher water use soils, 3 = alkaline and/or saline soils, and 4 = saline and infertile soils; crop type $k(k = 1, 2, 3)$ with 1 = alfalfa hay, 2 = corn for grain, and 3 = sorghum grain; applied water-yield coefficient $l(l = 1, 2, 3)$ with 1 = first two cuttings of alfalfa or low-water use for corn and sorghum, 2 = third cutting for alfalfa or midwater use for corn and sorghum, and 3 = fourth cutting for alfalfa or high-water use for corn and sorghum; water delivery state of nature $m(m = 1, 2)$ with 1 = inadequate canal water delivery and 2 = adequate canal water delivery; growing season precipitation state of nature $n(n = 1, 2)$ with 1 = dry, 2 = wet. Data sources, assumptions, and interpretation of each component of the DSSP model follow.

Soil and Agronomic Constraints ($R1$ and B)

About half of Crowley County irrigated acreage have productive soils and the other half saline-alkaline soils (Larsen, Martin, and Mayhugh). Soils were classified in the irrigated portion of the county into the four dominant soil associations ($R1, j = 1, \ldots, 4$). The most productive soils are 17,000 acres of loam, followed by 9,600 acres of sandy soil. For a given amount of applied water, yields on these sandy soils relative to the best soils are 25% less for corn and 10% less for sorghum (Larsen, Martin, and Mayhugh). Moderately alkaline and saline soils account for 16,400 acres and yield 80% of the most productive soil for alfalfa, 70% for sorghum, and because of corn's alkalinity intolerance, 60% for corn. The 4,500 acres of highly alkaline and saline soils are suited only for pasture and alfalfa and have yields that are 60% of yields from the best loam.

The agronomic constraint (B) was a recommended crop rotation for each soil. Alfalfa was rotated at least every six years with either corn or sorghum and alfalfa on the loam and sandy soils and every four years to maintain permeability on the moderately alkaline soils. Corn was rotated with either sorghum or alfalfa every four years for the loam and sandy soils.

Objective Function, Costs of Production, and Crop Prices

The objective function is expected regional income, with the region being defined as the acreage in Crowley County irrigated by the Colorado Canal. Specifically, the objective function is crop sales minus harvest costs ($C3$), planting costs ($C1$), and growing season costs and labor ($C2$). Thus the objective function maximizes expected annual regional return to the residual claimants of water, fixed capital (machinery), management, and land. Variable production costs (exclusive of irrigation water costs) obtained from alfalfa, corn (Dalsted), and grain sorghum[3] (Oklahoma State Extension Service) enterprise budgets costs were disaggregated into the following categories: (*a*) planting and preplanting irrigation costs for stage 1 activities; (*b*) growing season irrigation costs for stage 2 activities; and (*c*) the net of harvest costs and crop sales for stage 3 activities. Alfalfa establishment costs were amortized over the average stand life in southeast Colorado. Labor at $5.00 per hour was the only growing season irrigation cost because water costs are a fixed annual assessment. Volatility and inflation were removed from crop prices (Colorado Department of Agriculture) by taking a seven-year average of prices deflated with the GNP Implicit Price Deflator. The resulting prices were $73.38/ton for alfalfa, $2.46/bu. for sorghum, and $2.75/bu. for corn. Price risk was thus excluded, and only production risk was modeled. Production risk, however, determines the unique portfolio of crops planted in Crowley County compared with neighboring regions with identical crop prices but facing differing risk in irrigation water deliveries.

States of Nature and Irrigation Water Delivery Constraints

We assumed states of nature based upon the decision-maker's belief about an occurrence of an uncertain event and the evaluation of potential consequences (Anderson, Dillon, and Hardaker). Farmers' subjective probabilities for the second and third stages on water

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[3]In the absence of an irrigated grain sorghum budget for southeast Colorado, a budget from nearby Oklahoma was used.

diversions and precipitation were assumed to be derived from historical irrigation deliveries and rainfall. Irrigation shortages, when they occur, are in the mid to late summer. Inadequate irrigation water precludes a fourth alfalfa cutting and irrigation of corn after blister. The low priority water right of the Colorado Canal results in inadequate diversions 75% of the years (Ringle; Miles). The irrigation constraints for the adequate and inadequate states of nature ($R2$) are total Colorado Canal diversions. Diversions for the 30-year period averaged 89,700 acre-feet annually (Wheeler and Associates Inc.); 73,100 and 135,300 in the inadequate and adequate state of nature, respectively. The water available to farms is the water diverted less transit losses. Transit losses from main and lateral canals have averaged 31% of total diversions (as calculated from Wheeler and Associates Inc.).

Precipitation in stage 3 was aggregated into two states of nature. Approximately 60% of the years were below the mean (5.9 inches), averaging 4 inches of precipitation. The remaining 40% of the years were above average with 8 inches of growing season rainfall (Doesken). Diversion and precipitation events were assumed to be independent, as canal diversions from winter runoff and storage in distant mountains bear little relationship to summer rainfall.

Irrigation Water Input Coefficients and Crop Yields ($A1$ *and* $A2$)

Three irrigation levels corresponding to the amount and timing of irrigation within the region were incorporated as discrete points on corn, sorghum, and alfalfa production functions (i.e., $l = 1, 2, 3$). Thus, choice was allowed across crops, irrigation intensities, and soils. The typical response to limited irrigation supplies in the region is not to reduce water per application but, rather, to decrease the number of applications received by each crop. For alfalfa, fewer water applications result in fewer cuttings; for corn and sorghum, diminished yields. Analytic production functions relating applied water to yield have been derived for corn (Stewart and Hagan) and sorghum (Shipley and Regier) and were prorated downward (25%) to match actual reported farm yields for the best soils in the region. Corn was assumed to be irrigated four to six times with 5 acre-inches per irrigation. Sorghum was irrigated two to three times at 4 acre-inches per irrigation. A 4-inch preplant irrigation was necessary for corn and sorghum ($A1$) (Miles). The alfalfa production response was estimated to yield a maximum of four tons per acre for the best soils, with yield declining over the four cuttings by the ratio 4:3:2:1 (Miles; Tranel). Alfalfa was assumed to be irrigated after each of the four cuttings at 6 acre-inches per irrigation. Level and timing of irrigation water applications were assumed constant across wet and dry years as farmers can only estimate precipitation within the growing season. For all three crops, the contribution of effective precipitation under the two precipitation states of nature was subtracted from the total applied water requirements on the production function to obtain the irrigation water requirement.

Deterministic Static Linear Program

In contrast to the DSSP a deterministic single-period linear program (LP) was formulated:

(2)
$$\max \sum_{j=1}^{4}\sum_{k=1}^{3}\sum_{l=1}^{3} C_{jkl}\, X_{jkl},$$
$$\text{s.t.} \quad \sum_{k=1}^{3} X_{jkl} \le R1_j \quad (j = 1, \ldots, 4),$$
$$\sum_{k=1}^{3} B_k X_{jkl} \ge 0,$$
$$\sum_{k=1}^{3}\sum_{l=1}^{3} E(A_{kl}) X_{jkl} \le E(R2),$$
$$X \ge 0,$$

where E is the expectations operator, and thus $E[R2]$ is the mean irrigation diversion, and $E[A]$ is applied irrigation water under mean precipitation. The data used in the LP were the expected irrigation deliveries and expected crop production for each crop on each soil for each level of irrigation application with mean precipitation.

Validating the DSSP

The final step in the procedures was to validate the ability of the DSSP to predict irrigation demand. Validation was done by comparing the DSSP primal solution with regional cropping patterns as water was transferred from the county. The primal solution is the optimal land and water use mirrored by the dual values or shadow prices for these resources. Historic county crop mix and irrigated acreage provide an observed behavior to validate DSSP primal results. The year 1972 was chosen as a baseline: just before water transfers began and when Colorado Canal diversions were virtually equal to long-term mean diversions. In 1972, 46,200 acres of irrigated crops were harvested—15,500 in corn; 23,700 in alfalfa; and 7,000 acres in sorghum—with the remaining acres in minor crops (Colorado Department of Agriculture). Actual harvested acres and crop mixture approximated DSSP predictions. The DSSP predicted 43,000 irrigated acres with a crop mix of 32% corn, 58% alfalfa, and 11% sorghum (table 1). Under the assumed conditions, the DSSP showed 4,500 acres of the poorest soils would not be cropped. Only with above average irrigation deliveries did the DSSP predict the poorest soil to be cultivated.

Despite the water transfers, water-intensive alfalfa continued to dominate the actual cropping pattern in the county. By 1989, an estimated 60 to 70% of the original water rights had been transferred from the county (Flack). The actual irrigated acres of the major crops dropped by 60% to 18,300 acres: 6,500 acres of corn; 2,500 acres of sorghum; 9,300 acres of alfalfa (Colorado Department of Agriculture). At 35% of mean diversions, the DSSP predicted 18,100 cropped acres: 2,400 acres of corn; 200 acres of sorghum, and 15,500 acres of alfalfa. As was the case prior to irrigation withdrawals, predicted irrigated acreage approximated actual. However, predicted crop mix did not correspond as closely. The discrepancy was largely because of a court-ordered revegetation project in progress on previously irrigated land. To prevent dust storms and weed infestations, cities were required to revegetate land from which water was to be transferred. Under the ruling, alfalfa was prohibited and corn or sorghum was used as a cover to establish native grasses (City of Aurora).

Table 1. Optimal Crop Mix, Expected Regional Income, and Foregone Benefits

Percentages of Mean[a] Transfer Water Scenario	Deliveries Irrigation Constraint	Planted Acreage (thsd. acres) Corn	Alfalfa	Sorghum	Expected Regional Income ($ mil.)	Foregone Benefit[b] ($/ac. ft.)
DSSP Results						
50	50	2.8	22.4	1.4	3.2	27
65	35	2.4	15.5	0.2	2.2	31
75	25	0.0	12.4	2.1	1.6	33
0	100	13.6	24.7	4.6	5.5	37
LP Results						
50	50	13.6	6.5	0.5	3.7	29
65	35	10.6	2.7	0.0	2.6	35
75	25	7.6	1.9	0.0	1.8	40
0	100	13.6	24.7	4.6	6.0	43

[a]Irrigation deliveries for the DSSP scenarios are percentages of the mean deliveries (89,700 acre-feet) in the inadequate and adequate states of nature.
[b]Annual management and overhead costs of $46 per acre (Dalsted) are subtracted.

As Colorado Canal diversions decreased, low-valued, water-intensive alfalfa has continued to dominate the crop portfolio as compared with higher-valued and less water-intensive corn. In contrast, the predictions of the LP model regarding total irrigated acres and corn-dominated crop portfolio failed to anticipate this trend (table 1). When diversions are at the historic mean, the DSSP regional crop portfolio is equivalent to that predicted by the LP (table 1). As water is transferred, the LP predicts a crop portfolio dominated by higher-valued corn, a prediction typical of static deterministic linear programming models.

Results

Crop response to water shortage is the mechanism whereby risk is registered in farmers' decisions. The apparent anomaly that water-intensive alfalfa dominates the crop portfolio is the farmers' response to uncertainty. In Crowley County, the first and largest alfalfa cutting is assured by spring runoff diversions; subsequent harvests can be achieved if water supplies become available throughout the summer. In contrast, corn yield diminishes precipitously when late season irrigation is limiting. Sorghum responds to water shortages between the extremes of alfalfa and corn but is less profitable than corn. The relative response to water stress makes alfalfa the less risky choice when irrigation water supply is uncertain. This sequential stochastic production process portrayed in the DSSP primal results gives confidence in the dual solution of demand for irrigation water. From the demand for agricultural irrigation water the expected foregone agricultural benefits of agriculture-to-urban water transfers were then obtained.

Irrigation Water Demand

Dynamic decisions must account for previous decisions, uncertainty, and the effect present decisions have upon future decisions. Thus, factor demands in a sequential production process are a function of previous input quantities, expected output prices, and expected future input quantities (Antle 1988). In this case, demand for preplant through growing season irrigation water is determined by expectations of crop prices, precipitation, and irrigation deliveries. Of that list, only irrigation quantity can be affected by Colorado Canal decision makers through water sales or other policies and is thus pertinent to the discussion of demand and resulting foregone benefit.[4] Demand schedules for irrigation water diversions correspond to the two states of nature for diversions ($R2_m$, $m = 1, 2$).[5] The demand schedules in figures 1 and 2 illustrate stochastic irrigation water demand for Colorado Canal diversions, from which foregone benefits are then derived.

The most noticeable feature of irrigation demand in figures 1 and 2 is that inadequate diversions complement adequate diversions and vice versa. Farmers' value for adequate (inadequate) diversions water diminishes (increases) when expected diversions in the inadequate (adequate) years diminish (increase). Further, figures 1 and 2 show the relative responsiveness of demand for inadequate versus adequate diversions. The value of diversions in adequate years exceeds $120 per acre-foot when water is expected to be available in inadequate years as a complement. Demand for diversions in the adequate state of nature then falls off quickly. Conversely, the demand for inadequate diversions is more elastic and reaches $90 per acre-foot when adequate diversions are present to complement. When adequate diversions are 50% of normal, that water is valued at approximately $3 per acre-foot, given that inadequate diversions are also expected at 50% of average. In contrast, inadequate diversions are valued at $76 per acre-foot at 50% of average, given that inadequate diversions are also at 50% of average. Water supply in the inadequate state of nature is usually the binding constraint on crop production. When adequate diversions occur, the amount of water delivered exceeds agricultural needs and thus has no marginal value.

Cross sections of figures 1 and 2 are conditional demands and allow comparison of stochastic demand with deterministic demand derived from the LP in figure 3.[6] At the mean level of diversions for the two states of nature, an acre-foot of water in the inadequate state of nature is valued at $48 (fig. 3). In an adequate irrigation water year, 26,600 acre-feet go unused with a zero shadow price. At approximately 40,000 acre-feet of diversion, water value in the two states of nature is equal at approximately $80 per acre-foot. At the historic median diversion level of 87,000 acre-feet, the shadow price of water in the inadequate state of nature is $27 per acre-foot, compared with $9 per acre-foot for diversion in the adequate state of nature (fig. 3).

[4]Changing the probability of diversions would, in effect, change the seniority of water rights. Seniority of rights cannot be altered by local policy or by exchanges in the market.

[5]The demand schedules in figures 1 and 2 are derived from the DSSP by plotting the shadow price for diversions in the adequate state of nature (fig. 1) and diversions in the inadequate state of nature (fig. 2) obtained from parameterizing the constraint on diversions across intervals of 10% of mean diversions in each state of nature.

[6]The demand schedules in figure 3 are shadow prices of diversions at each basis changing irrigation deliveries ($R2$). The stochastic derived demands are conditional upon deliveries in the opposite state of nature being fixed at the historical mean.

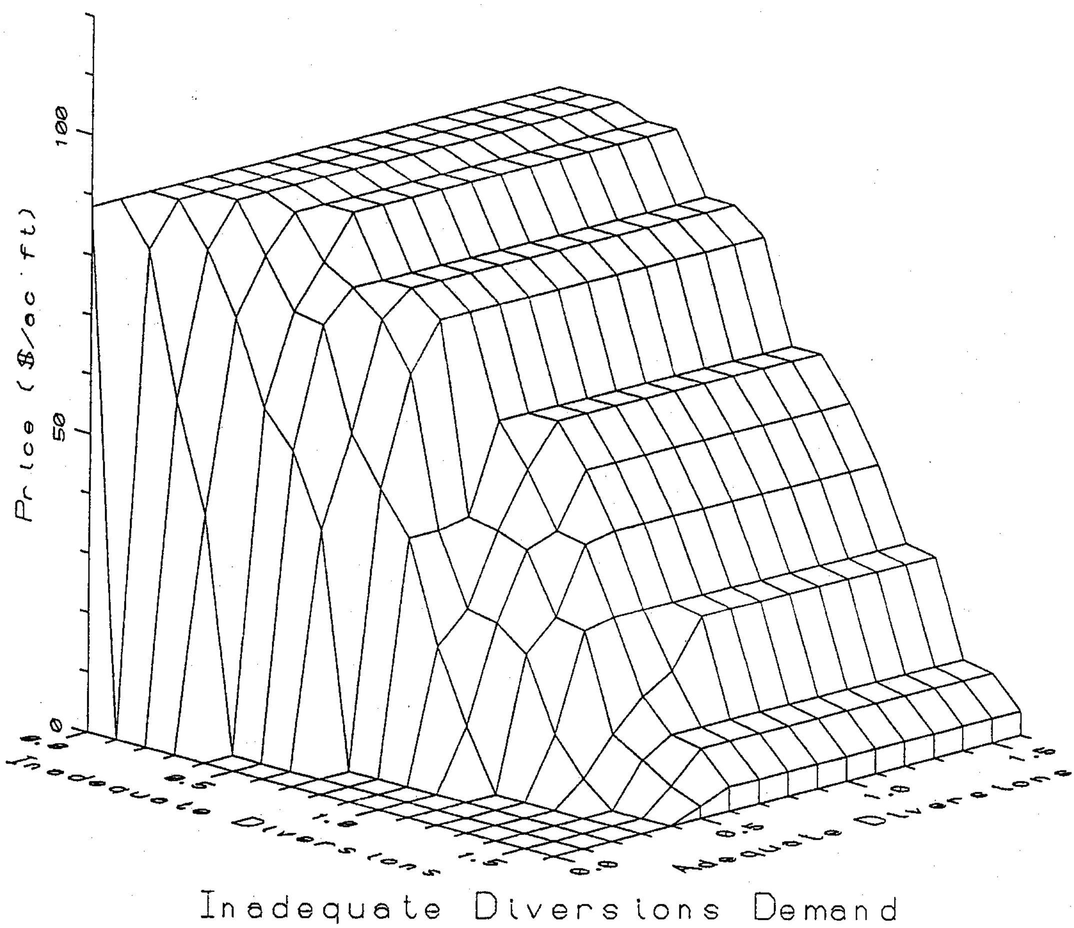

Figure 1. Demand for inadequate state of nature diversions: *Y* axis as price ($ per acre-foot) of inadequate diversions; *X* axis as own quantity, inadequate diversions (percent of mean); and *Z* axis as cross quantity, adequate diversions (percent of mean)

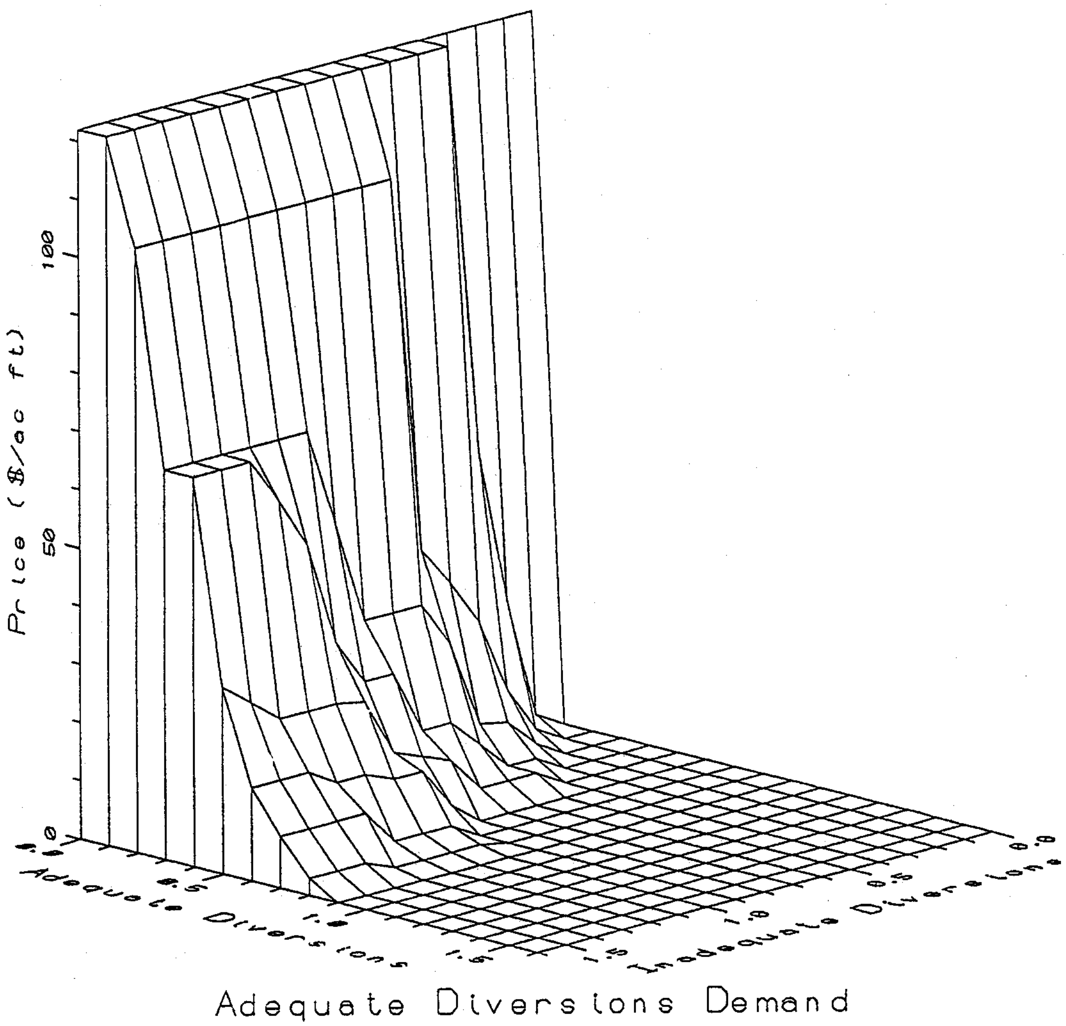

Figure 2. Demand for adequate state of nature diversions: *Y* axis as price ($ per acre-foot) of adequate diversions; *X* axis as own quantity, adequate diversions (percent of mean); and *Z* axis as cross quantity, inadequate diversions (percent of mean)

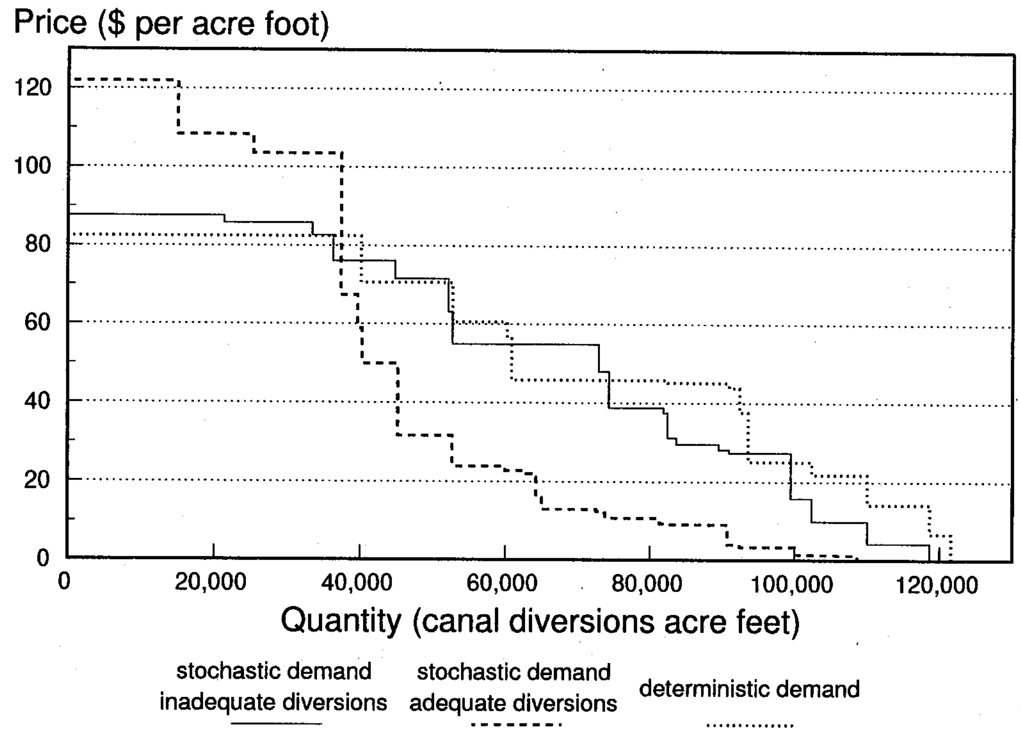

Figure 3. Stochastic versus deterministic demand for irrigation diversions

Risk Penalty

When risk is accounted for in a sequential crop production process, input-use efficiency declines (Antle 1988), which decreases the expected economic value for the stochastic input. Thus, the vertical distance between stochastic and static demand schedules is the payment needed for regional farmers to be indifferent about certain and uncertain irrigation deliveries or the risk penalty on irrigation water. Water provided with certainty is equivalent in value to water in shortage years as shown by the coincidence of derived demand from the LP model and demand for water in the inadequate years (fig. 3). The expected value of uncertain irrigation water supply, obtained by prorating the value of deliveries by probabilities of occurrence, is $25 per acre-foot (0.75 x $30 + 0.25 x $9). The risk penalty is thus $11 per acre-foot because at mean diversions irrigation delivered with certainty is valued at $36 per acre-foot. This example is based upon conditional demands and would vary if the adequate and inadequate demands were taken at different cross sections of the schedules in figures 1 and 2.

Direct Foregone Benefits

The nature of stochastic water demand has thus far been emphasized because the area under those demands provides the basis for estimating the foregone benefits of agricultural water use, namely, society's cost of agricultural-to-urban water transfers. The objective function, expected regional income, defines the area under the short-run demand schedules. Specifically, the foregone benefit of water is the area under the demand schedules in figures 1 and the DSSP objective function, declined from $5.5 million before water was withdrawn to $3.2 million after half of the water was transferred from the Colorado Canal (table 1).

To obtain the net residual value imputed to water, fixed costs must be subtracted from expected annual regional income predicted by the model. The fixed charge for management, land, and overhead of $46 per acre was obtained from area crop enterprise budgets (Dalsted). Fixed costs accrued on a per acre basis and thus the fixed costs for the acreage that corresponded to the amount of water purchased was subtracted to obtain benefits attributable to water only. Upon subtracting annual management and overhead costs from the area under the demand schedule, the estimated average foregone value of completely withdrawing of irrigation water from the county was $37 per acre-foot (table 1) or $0.11 per 1,000 gallons. Furthermore, a portion of this residual foregone benefit attributable to water is the risk penalty of agricultural water use. Akin to the vertical distance measure of a risk penalty in demand, the risk penalty for foregone benefit is the difference in areas under demand at comparable levels of withdrawals. For all the irrigation water from the Colorado Canal, the risk penalty is $6 per acre-foot ($43–$37, table 1).

Foregone benefit of water increased as increasingly valuable water was transferred from the county. Lower foregone benefit for initial increments of water transfers (e.g., $27 per acre-foot for half the water in the county versus $37 with a total withdrawal in table 1) reflect the lower value of foregone water on the poorer alkaline soils. The incremental water purchases were made or were withdrawn from poorer soils first, confirming the necessity of modeling soil associations.

The foregone benefit, as calculated above, mimics the present policy where water is withdrawn in equal percentage amounts in both adequate and inadequate years. As a policy alternative, a city could withdraw water in differing proportions in adequate and inadequate years and receive an identical amount of water. A policy of unequal proportions would alter expected foregone regional income. Complementarity in the demands shows that estimates of foregone benefits depends not only on the amount of water withdrawn in adequate (inadequate) years but also the amount expected to be withdrawn in the opposite inadequate (adequate) years. As an extreme example, the demand curves of figures 1 and 2 show all the water could be withdrawn in the inadequate years leaving the Colorado Canal with sizable expected deliveries in the adequate years, which are worthless in crop production. Cities contemplating lease agreements for unneeded water now encounter policies of water withdrawal.

Only the consumptive use (evaporation and crop transpiration) of Colorado Canal water can, by law, be transferred out of basin to protect other water users in the same basin. Transferrable consumptive use negotiated for the Colorado Canal was 75% (Knapp). Thus, the foregone benefit of consumptive water actually transferred from the county in a complete water withdrawal was $0.15 per 1,000 gallons.

Completing the comparison, direct foregone agricultural benefits are weighted against municipal benefits in comparable terms. Gibbon estimates a general marginal value of raw water in residential use in the western U.S. (derived by netting storage, conveyance, treatment, and delivery costs from retail price) at $0.90 per 1,000 gallons or $300 per acre-foot. Thus, raw water for residential use is several times the value of water in crop production. The relatively low value of irrigation water compared with urban use shows that market forces caused a lesser-valued water source to be used to meet emerging higher-valued water demands.

Conclusions

Colorado Canal irrigators must plant, irrigate, and harvest a portfolio of crops under limited and stochastic irrigation deliveries and precipitation. A regional model of irrigation demand must explain the stochastic sequential crop production to accurately predict the optimal crop mix. Optimal crop acreage from the DSSP was similar to actual crop acreage which assured accuracy in the derived regional irrigation demand. The result was that average foregone value of Colorado Canal irrigation water was estimated at $37 per acre-foot.

Risk reduced the value of Colorado Canal irrigation water by an estimated $6 per acre-foot. The reduction in water value due to risk varied with the quantity of diversions expected in adequate and inadequate years. Risk is reflected in benefit cost analysis by measuring uncertain benefits and costs to be matched with an appropriate rate to discount future costs and benefits. One conventional approach is to discount uncertain benefits and costs with a rate that reflects a degree of uncertainty. This study demonstrates that risk can be measured directly in foregone benefit as opposed to ad hoc methods which adjust the discount rate for risk. Further, risk does not necessarily increase costs but can have the opposite effect.

To compare marginal values in agriculture with marginal values in urban use, water was valued in comparable place, form, and time terms, that is, as raw water at the point of withdrawal. For a total withdrawal of water from the Colorado Canal, the consumptive use actually transferred adjusts foregone value to $0.15 per 1,000 gallons—considerably less than the marginal value of raw water in residential use. Thus, from the societal accounting stance, which made this nonmarket valuation necessary, the value of water in urban use overwhelms agricultural use. Further, it is doubtful that the absence of a risk penalty for agricultural water nor added transactions costs would be the deciding factor in the social benefit of transferring water from Crowley County agriculture-to-urban use. The market allocated Colorado Canal water to the highest-valued use. The relatively low value of water in irrigated agriculture that made the previous generation of agricultural water storage and conveyance projects economically questionable, now makes that same water vulnerable to urban transfer.

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